MECHANICAL REFRIGERATION FOR DOMESTIC USE

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CONTENTS

INTRODUCTION.

Mechanical refrigeration, or the artificial production of cold is a development of the nineteenth century. Many methods have been tested out and only a few have survived. Some were discarded because of the inadequacy of apparatus, while others were proven commercially impracticable.

The trend of development has been toward large production and larger units. Many of these large machines are giving very satisfactory service in producing ice to compete with natural ice, or in the refrigerating of storage buildings and manufacturing processes. Many processes have been made practicable by mechanical refrigeration, that were impossible when natural ice was the only available cooling agent.

Little if any attention has been given, until recent years, to the development of a small refrigerating plant for domestic use. Methods used in large plants have proven impracticable or undesirable in small units. The advent and spread of the central station supply of electrical energy has placed at the disposal of the householder a cheap, clean and constant supply of power. This thesis was undertaken to test out some methods, suggested by Prof. M. C. Beebe, of the Electrical Engineering department, for the utilization of electric power in the operation of a small unit refrigerating plant for domestic use.

CHAPTER I

HISTORICAL REVIEW.

The art of refrigeration is nearly as old as history. At first it consisted only of preserving or storing natural ice or snow for use in warm weather. This process was limited to climates where natural ice was found for at least a part of the year. There are a few historical references to the transportation of natural ice to warm climates for the use of royal families. Proper transportation facilities were lacking so that the expense was almost prohibitive.

Underground storage was one of the first methods used. A large circular excavation was made, usually about 30 feet deep and 30 feet in diameter at the top, tapering down to 10 or 15 feet in diameter at the bottom. Into this hole were packed alternate layers of snow and leaves. Over the top was built a thatch hut. Some means of removing the water from the bottom of the pit was often provided, either by natural drainage or manually.

Ice houses were soon built. Leaves and straw were used to pack and protect the ice but under the best of conditions it was almost impossible to store ice all summer.

In some localities the nights are cold even when the days are exceedingly hot. People soon discovered that if water was allowed to evaporate it was cooled, and that by exposing shallow pans of water to the cold night air ice would be formed. Considerable use was made of this method of ice making where

the climatic conditions would permit. The amount of ice obtainable by this method was very small and it was not long before improvements were made. One of the most successful devices consisted of a flat surface on which the water to be frozen was thrown in a fine spray. Evaporation of the spray was rapid so that when the water dripped over the edges of the flat surface it was cool enough to freeze and form icicles. Under favorable conditions quite a supply of ice could be obtained by this method. It was however necessary to remove the icicles before sun rise in order to preserve them for the day's needs.

It was only natural, then, that during the period when such rapid advances were made in machinery of all kinds that some effort should have been made to produce refrigeration or cold by mechanical means. The first refrigerating machine of which there is any notice, is one invented by Dr. Gorrie at New Orleans in 1845. It was an air machine, patented in England in 1849 and constructed with the intention of making ice. It was not very successful and in 1875, Sir William Siemans was asked to examine it and discover if possible the reasons for its failure. Sieman's report was detailed and lengthy. It was published in the Proceedings of the Civil Engineers[1] and is the first published work on the theory of refrigeration. Dr. Gorrie's machine had a compression cylinder in which the air was compressed, and from which it passed into a water cooled chamber. The air was partly cooled during compression by the injection of water, so that what passed into the receiver was really air and water together. The receiver pressure was maintained at about 15 pounds per square inch above

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1. Min. Proc., Inst. C.E. Vol. lxviii, 1882, p. 179.

atmospheric pressure. The water settled out in the receiver and the cool dry air was drawn into an expansion cylinder. During expansion the air performed work on the piston at the expense of its sensible heat so that its temperature was lowered. During expansion a certain amount of brine was injected into the expansion cylinder and the low temperature of the air was communicated to it by direct contact. The air was exhausted directly into the armosphere while the brine, which had been cooled to about 20° Fahr., was conveyed to a tank and usefully applied to ice making or other refrigerating purposes.

Siemens pointed out that only a small part of the available refrigeration was used because the cold air was allowed to escape into the atmosphere. He suggested using the exhaust air to cool the incoming warm air. The cool air would be led thru a series of pipes around which the incoming air would flow. In this way the cold of the exhaust air would be partly saved by reducing the temperature of the incoming air. This interchanger of Siemens is the first example of the regenerative principle applied to refrigerating machinery. It is now found in one form or another on several of the different types of machines.

In 1862 Dr. Alexander Kirk produced a practical machine of the closed cycle type. This differs from the method of Gorrie, in that the air is used over and over again, repeating a definite cycle. In theory it is simply a Stirling air engine working reversed, that is working as a heat pump instead of working as a heat engine. Kirk began by constructing a small model. The

substance to be cooled was placed in a cup at the top. The air was pumped back and forth thru a regenerator by means of a hand pump. The air when compressed was cooled by a circulation of cold water. With this model Kirk was able to freeze mercury in the cup. After this Kirk constructed several large machines. His immediate purpose was to construct a machine for the extraction of paraffin from paraffin oil. This was carried out successfully at the Bathgate Paraffin Oil Works. Several similar machines were built. One of them worked for a number of years in an ice factory in Hong Kong. It is recorded that this machine produced 4 pounds of ice per pound of coal. This type of machine is now obsolete. It was experimented with extensively by the American inventor, Allen and the German, Windhausen.

A practical open cycle air machine was brought out by Gifford in 1873. It was afterwards modified by several English inventors, prominent among whom were Bell and Coleman, Lightfoot, Sir Alfred Haslam, and Messrs. Hall of Dartford. In 1878 the steamer Strathleven was equipped with a machine of this type to bring frozen meat to England from Australia. The experiment was a success and has led to an enormous business.

The main features of the type of machine used are the same as those of the Gorrie except that no water or brine is injected into the cylinders and the air is used for cooling directly. This type was more satisfactory for cooling rooms or buildings than for ice making. As a general thing the air machines were not very successful but served to advance the art of refrigeration.

As early as 1810 Prof. Leslie described a laboratory experiment in which a saucer of water was frozen by placing it under the receiver of a vacuum pump with another saucer containing sulphuric acid, and exhausting the air. The low pressure and rapid absorption of the water vapor by the acid caused the water to be cooled because of the rapid evaporation. This is the basis on which Windhausen worked when building an ice making machine for the Aylesburg Dairy Co. in 1878. The chief difficulty in developing an efficient process was the fact that the acid because diluted after a little use and had to be renewed or concentrated before the process could be repeated. Windhausen used a concentrator in which the dilute acid was heated to drive off the water. The process was thus made continuous. A heat interchanger was used to warm the cold dilute acid as it was entering the concentrator and cool the warm concentrated acid as it was leaving. The capacity of this machine was about 12 tons in 24 hours. A compound air pump maintained a vacuum of only 1/20 pound per square inch.

At about this time Mr. E. Carre invented a small absorption machine for domestic use. It was hand operated and embodied a device for agitating the acid by means of a stirring rod linked to the pump handle.

In 1860 F. Carre produced an absorption machine using ammonia. The ammonia was driven off of a concentrated solution of ammonia and water by heating. The ammonia vapors were condensed and expanded thru a valve into a chamber where they were absorbed by a dilute ammonia liquor. The process in the original

machine was intermittent but improvements contributed by Messrs. Reece, Stanley and Mart made the process continuous by means of a concentraterand interchanger. Many machines of this general type were built. In Louisville a central refrigerating plant was installed using a Sulzer-Vogt machine. The concentrated liquid ammonia was distributed thru mains under the streets to the houses where it could be drawn at will. The expanded gas was drawn back to the station thru a return main. The use of an absorption machine gave very uniform operation at the station regardless of the fluctuations in comsumption.

The vapor compression type of machine is the latest and today the best. It is quite similar in form to the Belle-Colman air machine but an expansion valve is used in place of an expansion cylinder. The first machines of this type were built by Southby and Blyth. They used water vapor. It was found that such a large volume of water vapor had to be handled that the machine was cumbersome and bulky and the friction losses excessive. Various substances were substituted for water. Of these sulphurous acid, ammonia, and carbonic acid are the most important. The vapor pressure of sulphurous acid is below atmosphere at low temperatures so that a vacuum machine is necessary. That of carbonic acid is always above atmospheric and is very high at ordinary temperatures. The vapor pressure of ammonia is always above atmospheric but does not rise very high thru the range of operating temperatures. From this standpoint ammonia is the best but it has a very disagreeable odor. All three vapors have been used successfully and some builders

favor one and some another. The vapor compression type of machines give the best refrigerating efficiency and are in most common use today.

CHAPTER II

PURPOSE.

There are three reasons why a small compact electrically operated refrigerating machine would find favor with the general public. At the present time practically all of the household refrigeration depends upon a daily supply of national or, in some few cases, artificial ice from the ice man. If the ice man depends on lakes and rivers for his season's supply he may not always be able to furnish the ice required. Failure of the ice crop is not an uncommon thing. If the winter is warm the ice does not freeze thick enough to cut and if the winter is cold there may be so much snow that harvesting is difficult or absolutely impossible. Then after harvesting, the ice must be stored and sometimes shipped. There are large unavaoidable losses involved in storing and transporting. Ice houses seem to be very liable to destructive fires and the entire local crop may be ruined by the destruction of the ice house. It is therefore evident that the daily supply of ice to the kitchen refrigerator is liable to interuption from several different things.

The second reason in favor of mechanical refrigeration is the dirt and bother of ice refrigerator filling, which is obviated. The process of placing the ice in the refrigerator is usually difficult and the attendant drippings and mess are objectionable. Then again there is no ice that does not leave slime in the refrigerator when it melts. Even the purest artificial ice is not free from this criticism. Mechanical

refrigeration would obviate the periodical replenishing of the ice supply and no dirt or slime would be introduced into the compartments. These two reasons are seen solely from the point of view of the house keeper. There are other people interested however.

The electric central station company is supplying electrical power for lighting and power. In residence districts the load is mainly lighting, and therefore is heavy in the evening and very light the rest of the time. The equipment is therefore not being used to the greatest advantage and the cost of supplying the power is not a minimum. Any kind of a lighting or power load during the day would increase the efficiency of the system. Electrically operated refrigerators would be an almost ideal day load. In the ordinary house a mechanical refrigerator could be operated during the day time and furnish enough cooling for the whole 24 hours. This kind of a uniform day load is very much desired by the central station companies and would probably lead to an especially favorable rate. The cost of electric power for refrigeration, equivalent to that obtained from ice should be less than the cost of ice, unless the ice supply is very close and plentiful.

The primary purpose of these experiments was to develop a satisfactory machine to furnish an electrical day load. In order to be practicable the refrigerating machine must be reliable and simple. To make it desirable for house use the noise and odors must be a minimum. Simplicity is placed above efficiency because little skilled attention can be expected

and the fewer parts to get out of order or need attention the more reliable will the machine be.

CHAPTER III

GENERAL THEORY

There are two ways of producing cold, one is by chemical combination and the other is by means of some form of heat pump. The chemical combination of substances has long been used to produce low temperatures for laboratory use. An example of this sort of cooling that is found in every day use is the mixing of salt with ice to freeze ice cream. The chemical affinity of salt for water is so great that it will cause the ice to melt at temperatures below freezing. In melting the ice must absorb sufficient heat to supply the latent heat of fusion. The only heat available is the sensible heat of the ice so that the temperature is reduced. There are numerous combinations of chemicals that interact in this way. One of the best is calcium chloride with carbonic acid snow. Temperatures as low as -166° F. have been obtained in this way. Altho very low temperatures are easily obtained by chemical means, the method is commercially impracticable and is used almost exclusively in laboratory work.

Heat pump machines use a gas as the working substance. Some machines are designed to operate at pressure at which the working substance is always a gas while others operate at pressures at which the working substance is a gas for part of the cycle and a liquid during the remainder. The action depends upon the kind of working substance used.

If air is the working substance no liquification is possible.

It may be compressed in any kind of a pump. It is then cooled as much as possible at the high pressure. There are two ways of expanding the air, one by means of an expansion cylinder and the second by means of a valve. In the first case the air at high pressure is drawn into a cylinder. The cut-off is short, so that the expansion is great. Work is done on the piston during expansion. The process is nearly adiabatic, so that the work is done at the expense of the sensible heat. The work done on the piston may be utilized in compressing more air. This is a saving that is quite important in large size machines.

The air may be expanded thru a valve . The temperature is reduced but not as much as when external work is done. The only work done is internal so that the reduction in temperature is quite limited.

The boiling point of ammonia and some other substances is within the range of working temperatures of refrigerator machines. When one of these substances is used the refrigerating effect per unit weight of material is greatly increased because of the latent heat of vaporization. In the vapor compression machine for instance the vapor is compressed in some sort of a pump. Some of it condenses in the pump and the remainder is liquified when cooled in the condenser. The liquid under pressure is expanded thru a valve. The low pressure causes the liquid to evaporate. Heat of vaporization is necessary and the only heat available is that of the liquid and gas. The temperature is therefore reduced. The cool vapor may be used to cool brine or compartments but it must be retained in the closed system of the machine. This is very

necessary if the working substance is dangerous or disagreeable as are ether and ammonia. When the vapor has accomplished its purpose, it is drawn into the pump and compressed again. Vapor compression machines are invariably closed cycle machines because the working substance is usually too expensive to waste after only one cycle.

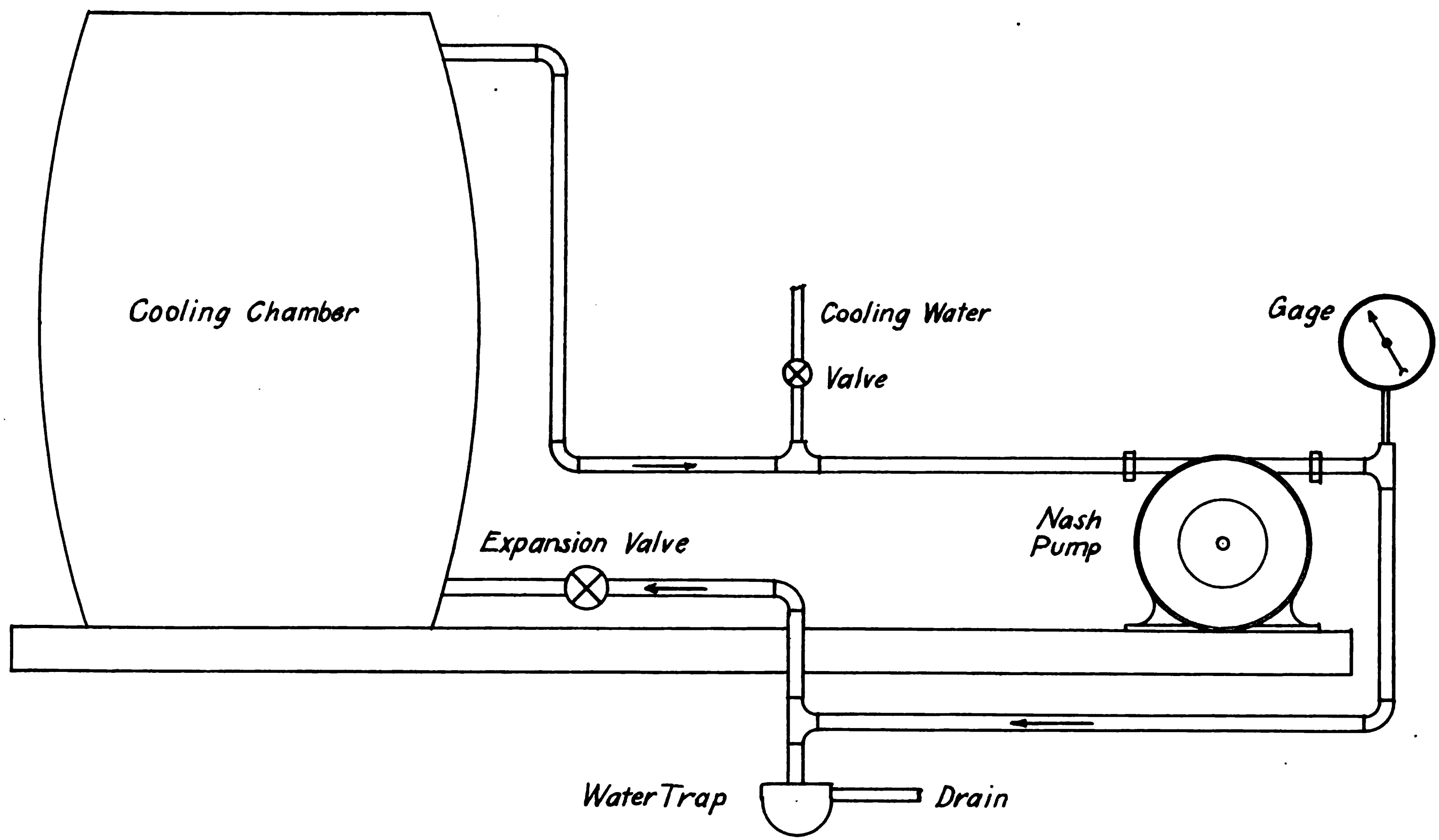
Cooling Chamber
Cooling Water
Valve
Gage
Expansion Valve
Nash
Pump
Water Trap
Drain

Figure 1.

CHAPTER IV

METHODS, APPARATUS, AND OPERATION.

The first device tested, is shown diagramatically in Figure 1. The cooling chamber is a large barrel and the working substance is air. The pump is a Nash centrifugal, rated at 10 cu. ft. per minute, driven by means of a belt and a 1 H.P. electric motor.

The theory of operation is as follows: The air is drawn from the top of the barrel thru the pipe to the pump. Before reaching the pump the air is mixed with cool water which is introduced thru a control valve. The pump receives water and air and compresses the air. The heat of compression is absorbed by the water which has a much higher specific heat than air. At the lowest point in the system a water trap is provided to drain off the water as it separates out of the air. The dry air passes on thru the expansion valve into the bottom of the barrel. The air entering the barrel is cooled by means of the work done in expanding thru the valve.

It was realized that the cooling effect of such a device would not be large but it was hoped that the type of pump used would compress a sufficient quantity of air to give enough cooling to be practicable. The results of tests run on this device proved it to be entirely inadequate. Several practical difficulties were alse encountered. The velocity of the air thru the pipes was so great that only a very little of the cooling water separated out. The result was that it collected

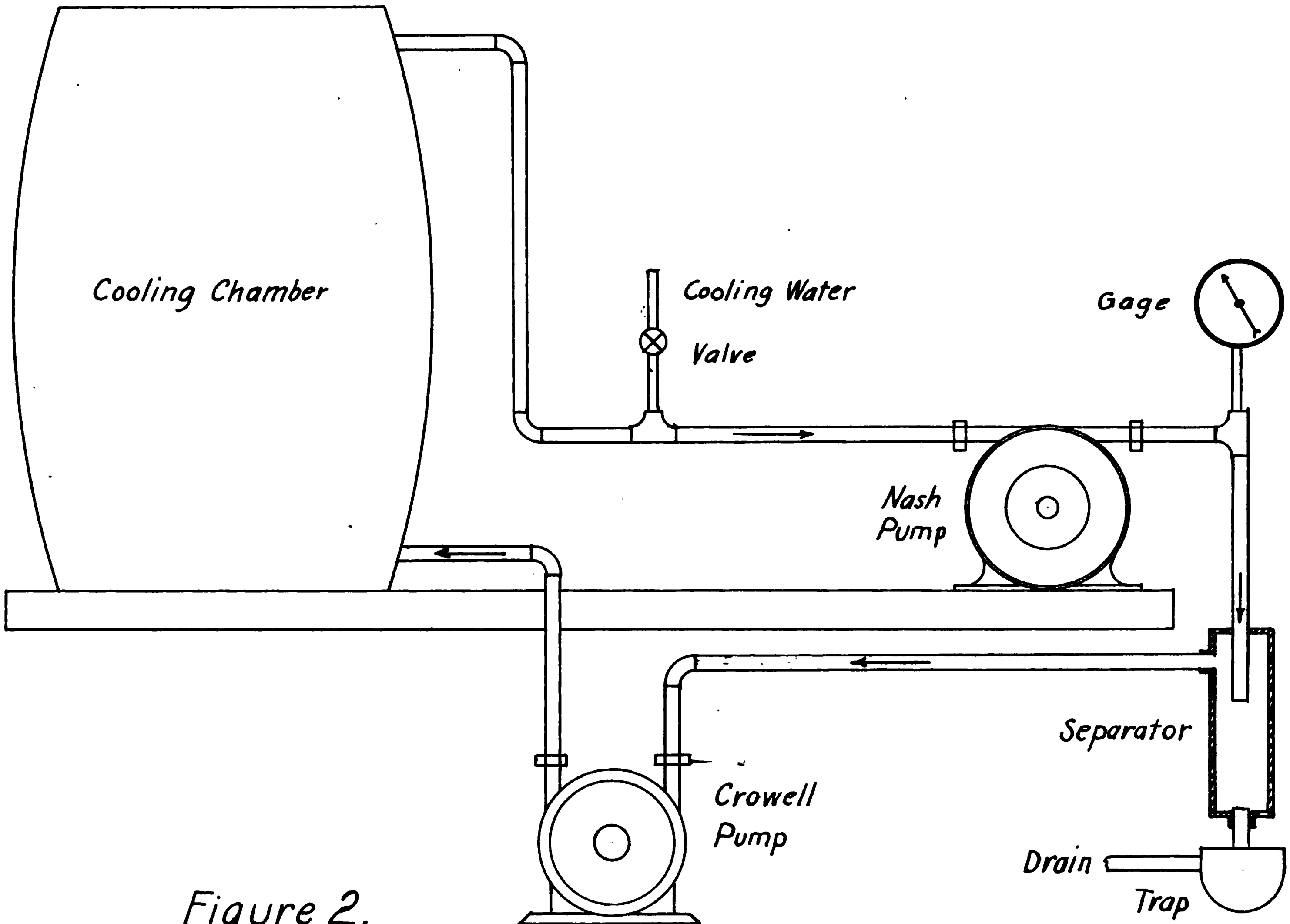
Cooling Chamber
Cooling Water
Valve
Gage
Nash Pump
Separator
Crowell Pump
Drain
Trap

Figure 2.

in the barrel and prevented free expansion of the air. Leakage of air from the system on the high pressure side so reduced the pressure in the barrel that the water was drawn in to take its place. By opening the barrel to atmospheric pressure at the top this latter effect was remedied. Under the best of conditions the reduction in temperature of the barrel below room temperature was not more than 5° F. The maximum pressure obtainable with this pump was only 20 lbs. per square inch above atmospheric. This pressure was produced when the expansion valve was closed and no air was circulating. The pressure dropped off rapidly as the valve was opened. The quantity of air circulated with the valve opened wide was not very great so that the cooling effect was very limited.

In order to separate out the cooling water more completely a separator similar to those used in steam lines was constructed of pipe fittings. A diagramatic sketch of the improved device is shown in Figure 2. In place of the expansion valve in Figure 1 a Crowell rotary vane air pump was placed. This was to run as a motor and expand the air by letting it do work. The separator proved to be quite satisfactory and little trouble was experienced with water passing over into the motor.

The machine as a whole failed to operate because the pump could not compress enough air to a pressure sufficient to drive the air motor. Efforts were made to drive both the pump and air motor by means of the electric motor but inability to obtain the proper speed relations between the various elements prevented stable operation.

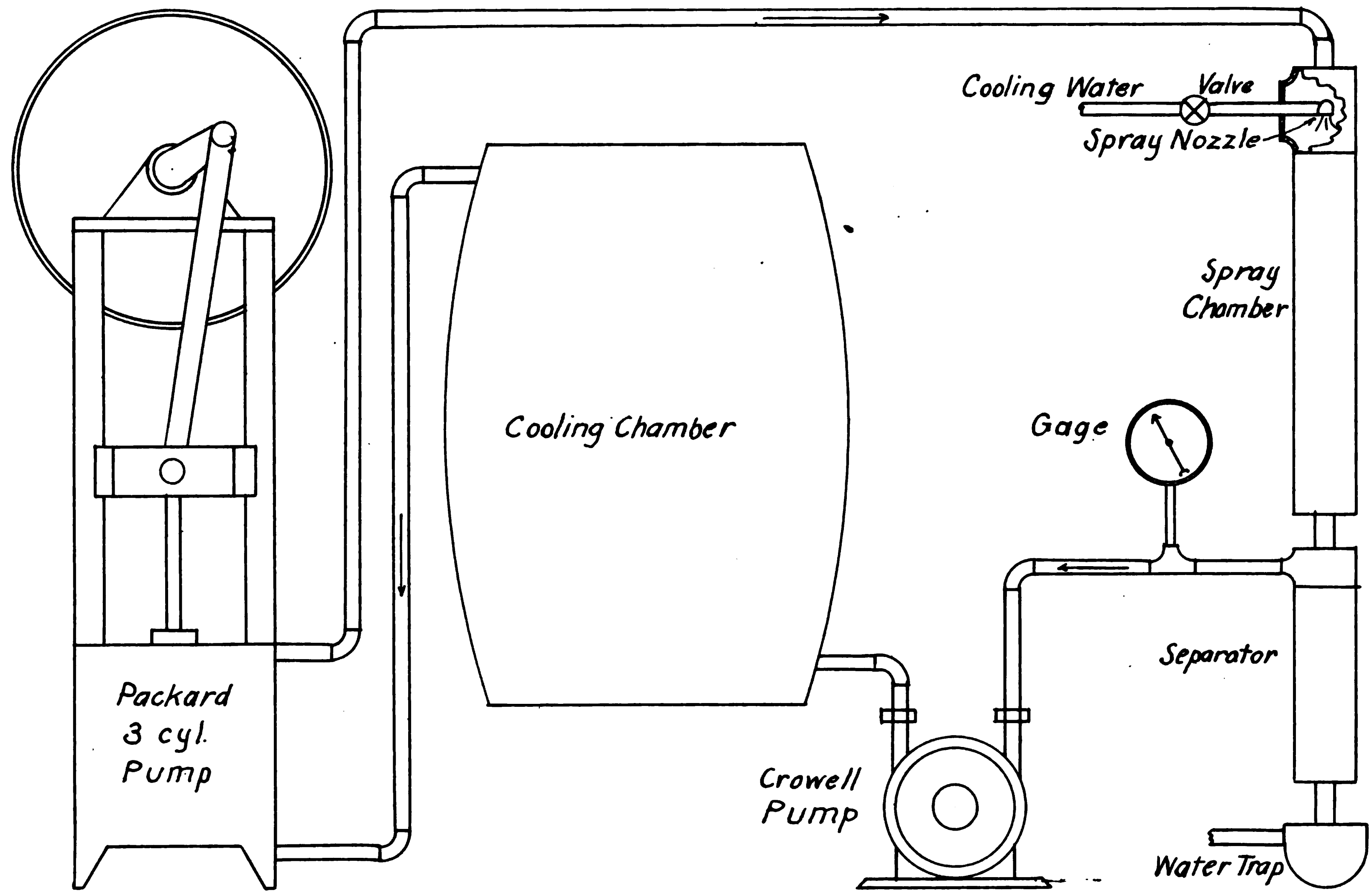
Cooling Water
Valve
Spray Nozzle
Spray Chamber
Gage
Separator
Water Trap
Crowell Pump
Cooling Chamber
Packard 3 cyl. Pump

Figure 3.

The entire apparatus was then rearranged as shown in Figure 3. A three cylinder Packard vacuum pump was substituted for the Nash centrifugal pump. This pump has three vertical double acting cylinders of $4\frac{1}{4}$" bore and 6" stroke. The crank shaft is mounted at the top of the frame and the cylinders at the bottom in a cooling reservoir. The inlet valves are in the bottom of the cylinders. Air is drawn in on the upward stroke of the piston and forced thru valves in the piston into the upper chamber on the return stroke. The next upward stroke exhausts the air thru automatic valves in the top. After passing thru an oil separator the air is led out and up to the top of the spraying chamber. It is impracticable to pump the cooling water thru with the air so it is sprayed in after the air has been compressed. The water separator, trap, air motor and barrel are arranged in the same manner as before. Pressures up to 40# per square inch were obtained with this pump, operating at about 120 r.p.m. In order to expand the air, the motor had to turn at 1000 r.p.m.

This combination of elements operated quite satisfactorily and a cooling effect of 10 - 12° F. was obtained. Due to the large amount of piping the heat leakage was probably very large, thus reducing the effect. Altho this machine was an improvement over the first two devices it was impracticable because of the bulk of the pump and the noisy operation. The efficiency was also very low, about 1.5 Kw. being required by the electric motor to drive the pump.

This completed the experiments using air as a working

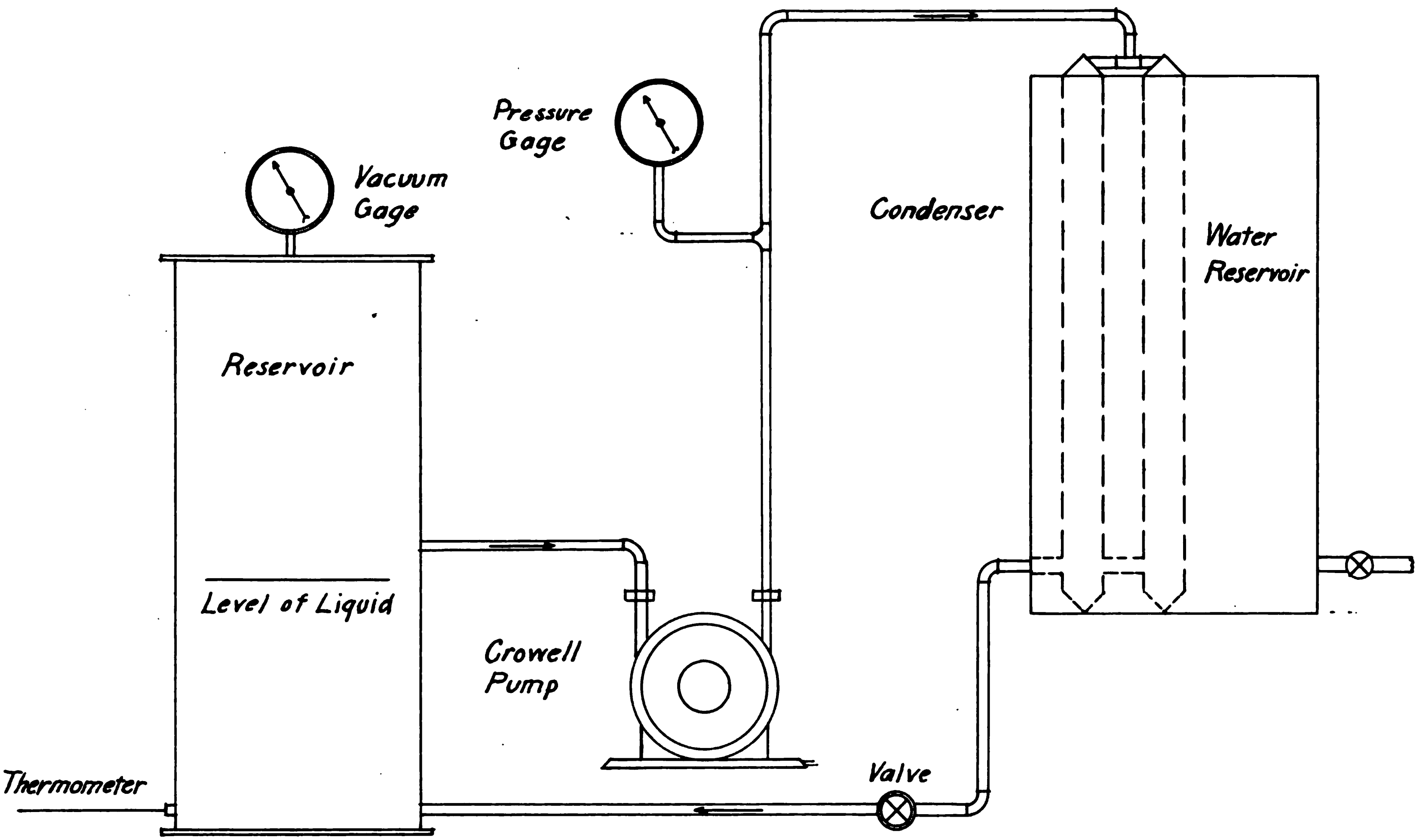
Pressure Gage
Vacuum Gage
Condenser
Water Reservoir
Reservoir
Level of Liquid
Crowell Pump
Thermometer
Valve

Figure 4.

substance. The use of ammonia has proven quite satisfactory in general practice, so it was considered next. The scheme of the apparatus is shown in Figure 4. The reservoir is about a foot in diameter and 3 feet high. It is partly filled with concentrated ammonia. (NH_4OH) The pump draws off the ammonia vapor above the liquid and compresses it. The condenser consists of cooling pipes surrounded by water in which the ammonia vapor is cooled and condensed. The liquid ammonia then passes thru the expansion valve back into the reservoir. Theoretically the ammonia should evaporate under the reduced pressure maintained in the reservoir and thus cool it. In actual operation the ammonia did not vaporize and the cooling effect was therefore small. The greatest cooling effect obtained with this equipment was about 20°F. The apparatus was not insulated in any way so that the heat leakage was probably large. The effect of dilution of the ammonia with water was to reduce the cooling.

Some difficulty was experienced when liquid was drawn over into the pump. The rotary vane pump built by the Crowell Mfg. Co. was used for this test. It will compress gas very nicely but if liquid is mixed with the gas the pump is subjected to severe strains due to the inelastic qualities of a liquid. It was thot that a circulation of the liquid ammonia with the vapor might be an improvement. The apparatus was rearranged as shown in Figure 5 and the Nash centrifugal pump substituted for the rotary pump in order to accomodate the circulation of the liquid.

This arrangement of elements produced no cooling effect

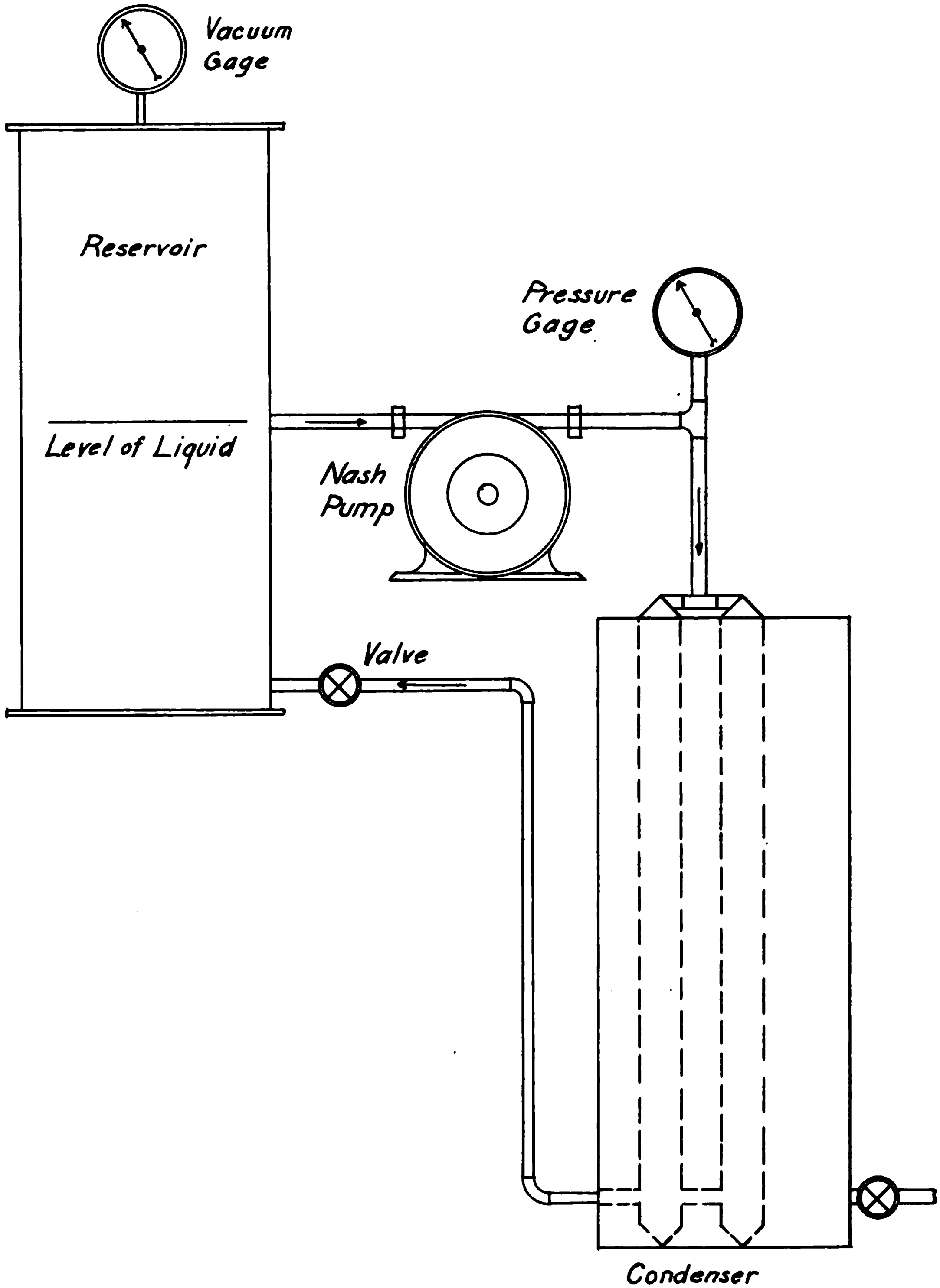
Vacuum Gage
Reservoir
Pressure Gage
Level of Liquid
Nash Pump
Valve
Condenser

Figure 5.

whatsoever. The pump was entirely inadequate. The pressure developed was so low that almost no circulation occurred.

CHAPTER V

CONCLUSIONS.

The results of the experiments were so far from being completely satisfactory that no very definite conclusions can be drawn.

The expansion of air in a valve to produce refrigeration is evidently quite unsatisfactory. This is explained by the Thomson-Joule theory which states that the internal work done in a gas during expansion depends upon the relation of the operating temperature and pressure to the critical temperature and pressure of the gas. At ordinary temperatures the Thomson-Joule effect of air expanding thru a valve is only $\frac{1}{4}^{o}$ C. per atmospheric difference of pressure.

The use of air as a working substance has many advantages. It is odorless, non corrosive, non explosive and does not damage anything with which it comes in contact. It is plentiful so that no care need be taken to prevent leakage or loss to preserve the supply. The disadvantages of air however outweigh the advantages. Very little cooling effect is produced per pound of air compressed. The heat carrying ability of air is small. Such large volumes of air must be pumped to secure a given cooling effect that the pumps are cumbersome and heavy and successarily inefficient.

Ammonia gives much better refrigeration because of the fact that it can be liquified at ordinary temperatures by pressure alone. In evaporating it must absorb enough heat to supply

the latent heat of vaporization. At 25# pressure the latent heat of vaporization is 588 B.t.u. per pound and at 5# pressure it is 633 B.t.u. The lower the pressure at which vaporization takes place the greater amount of heat per pound will be absorbed.[1] The thermodynamic properties of ammonia are therefore quite satisfactory. Ammonia is however very disagreeable to work with. The odor is bad and there is danger of suffocation from breathing the fumes. Ammonia corrodes brass and bronze but not iron or steel. It is quite expensive and must therefore be preserved. This is made easier by the fact that leaks are readily located by smell.

The tests performed with ammonia as the working fluid show that it is more satisfactory than air at pressures below two atmospheres. Altho not conclusive the results give reasons to believe that a successful machine can be developed along the lines followed.

Mendeleeff[2] the Russian Chemist describes an ice making machine of Carre's, which altho crude in form and intermittent in operation was successful. It consisted of a stove, a pair of reservoirs connected by a tube at the top, and a water reservoir. One of the reservoirs was partly filled with a solution of ammonia and water. This was placed on the stove, while the other was submerged in the cooling water. The heat from the stove drove off the ammonia in vapor, which was condensed in the cool reservoir because of the high pressure of the vapor

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1. Reyes and Brownlee, Thermodynamic Properties of Ammonia.
2. R. Mendeleeff, "The Principles of Chemistry", Vol. I, Ch. VI, Note 7.

and the lower temperature of the surrounding water. When a temperature of about 130° C. was reached almost all of the ammonia was distilled over. The heated tank was then put in the water and the other removed. The great chemical attraction between ammonia and water caused the vapors to be absorbed and the pressure lowered. So rapid was the absorption that the pure liquid ammonia was rapidly evaporated. The amount of heat absorbed during this process was sufficient to lower the temperature in that reservoir enough to make ice.

The theory of the device tested is similar to that of Carre, with the additional purpose of making the process continuous. The first device as shown in Figure 4 gave the best results of any. The cycle of operationsare identical. The pump and condenser replace the stove and condenser of Carre's machine. No water need be used in solution with the ammonia because the vacuum is created by the pump instead of by absorption of the vapor.

There is still room for considerable experiment and development of the domestic refrigerating machine. The experiments so far performed show more what cannot be done along certain lines than what can be accomplished along any line. The problem is a long way from being completely solved but gives promise of success along the lines worked by Carre.

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APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

M C Beebe

June 14, 17